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APPLICATION OF MCDA/MCDM METHODS FOR AN INTEGRATED URBAN PUBLIC TRANSPORTATION SYSTEM – CASE STUDY, CITY OF CRACOW

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Abstract:

The paper presents the application of the Multiple Criteria Decision Aid/Making (MCDA/MCDM) methodology in the assessment of the development of different scenarios for an urban public transportation system (UPTS). This methodology allows considering several conflicting objectives and performing the evaluation process in a comprehensive manner. This approach also corresponds to the holistic philosophy: different aspects (economic, technical, social etc.) and interest groups – stakeholders (operators, passengers, city government etc.). The MCDA/MCDM methodology is specifically customized to the real life case study – urban public transportation system in the city of Cracow (Poland). A family of 10 criteria is proposed to evaluate several solutions (W) for a UPTS in terms of their usefulness and attractiveness for different stakeholders. These criteria take into account: travel time and standard, effectiveness of the fleet use, environment friendliness, the level of integration and reliability of the UPTS, safety and security, the profitability and availability of the UPTS, investment costs. Considering the possible solutions, the 6 alternatives were designed heuristically and compared with the current state (denotation of alternative W0). Based on the analysis, for the final considerations compared with the current alternative, 7 new solutions of the integrated urban public transportation in Cracow were adopted, denoted as: W1 (bus/rail alternative: integration of high-speed agglomeration rail with bus transportation), W2 (rail/tram/bus alternative: integration of high-speed agglomeration rail with tram and bus transport system), W3 (alternative with the underground: integration of the underground with high-speed agglomeration rail and with tram and bus transport system), W4 (tram/rail alternative: integration of high-speed agglomeration rail with tram transport), W5 (Tram alternative: integration of tram transport with bus transport), W5A (tram alternative: sub-alternative to the alternative W5, integration of tram transport), W6 (dual-mode tram alternative: integration of dual-mode tram transport).
The variants of the scenarios for the urban public transportation system were generated by VISUM computer macro-simulation software. The computational experiment was carried out with the practical application of different Multiple Criteria Decision Aid/Making methods: AHP (Expert Choice program) and Electre III (software package Diviz).

Key words:
multi criteria decision making, public transportation integration, transportation planning, transportation simulation

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1. Introduction

In Poland, the problems of urban transportation in local government units at various levels are subject to a number of changes. Due to their nature, researchers more and more frequently use simulation tools in order to identify potentially occurring phenomena (Basaric *et al.* 2015; Baurer and Szarata 2013; Bischoff and Maciejewski 2016; Bocarejo *et al.* 2016; Horni et al. 2016; Karoń *et al*. 2010; Martínez *et al*. 2017; Sawicki *et al.* 2016; Szarata 2014). It is undeniable that the decision problems of urban/agglomeration /metropolitan sustainable transportation are characterized by high complexity (Buehler *et al.* 2017; Jeon et al. 2010; Sawicki *et al.* 2016; Schmidt 2014; Vermaand and Ramanayya 2014; Zegeas and Rayle 2012; Vaidya 2014; Vuchic 2007). It results from the fact that they have an effect on a number of stakeholders. Besides, what is emphasized in numerous approaches, while solving these problems, many economic, technical, social and environmental aspects should be taken into consideration (Bojkovic *et al.* 2010; Ceder 2015; Kiciński *et al.* 2017; Mardani *et al.* 2015; Merkisz-Guranowska and Stańko 2015; Vermaand and Ramanayya 2014). It is also important to take account of the conflicting interests and points of view of the participants in the decision-making process (e.g. city authorities, operators, community). Therefore, the methodology for multiple-criteria decision making/aiding (MCDM/MCDA) is increasingly being applied in solving complex, multi-faceted decision-making problems. There are many classifications of MCDM/MCDA methods. Hence, depending on the decision-making problem being solved, the following methods can be distinguished: choosing, ranking and sorting (Figueira 2005; Mardani *et al.* 2016; Doumpos and Zopounidis 2002). On the other hand, taking into account the methodological basis, common approaches can be divided into the following methods (Vincke 1992): multi-attribute utility theory, based on the outranking relation, and interactive approach. The paper describes and compares the two methods used for ranking alternatives, i.e. AHP and Electre III. These methods are used to resolve numerous identified multiple-criteria problems from the field of public transportation (Hsu 1999, Mardani *et al.* 2016; Perez *et al.* 2015, Salavati *et al.* 2016). They were used to rank the alternatives of the integrated urban public transportation system in Cracow (Poland).

2. Description of the applied MCDM/MCDA methods

2.1. The AHP method

The multiple-criteria AHP method (Analytic Hierarchy Process) was proposed by T. Saaty in 1980. It is based on the multi-attribute utility theory and allows the decomposition of a complex decision-making problem, which eventually allows ranking the finite set of alternatives (Saaty 1980). It is based on the key principles (Saaty 1980, 1990, 1995) that form the basis for the use of the algorithm. This process can be divided into four basic stages: construction of the hierarchy model (stage I), rating by pairwise comparison of criteria (sub-criteria) and alternatives (stage II), determination of global preferences (stage III) and final ranking of decision alternatives (stage IV).

In Stage 1 of the AHP method, a hierarchical decision tree is constructed representing the structure of the considered decision-making problem. It includes the goal of the decision-making process (level 0), the criteria (the sub-criteria, if applicable) (level 1) and the alternatives being rated (level 2).

Stage II involves determining the subjective preferences of the decision-maker and the interveners. At this point, it is necessary to adopt the Saaty's scale from 1 to 9, where, in pairwise comparison of criteria, sub-criteria and alternatives, 1 stands for the indifference of the elements, and 9 represents an extremely strong advantage of the first element compared to the second one. The intermediate values reflect the proportionate increase of the relative advantage of one element over another. All ratios are compensatory (pairwise consistency), which means that the rating value for the less important (less preferred) element in a given pair is the inverse of the value assigned to the more important (more preferred) element. As a result, the less important elements in the compared pairs are assigned the values of 1/2, 1/5 or 1/7. Based on those specific ratings, at every level of the hierarchy, square matrices of preferences A are created (e.g. the matrix of weights for the alternatives relative to a given criterion) Then, for each matrix of relative weights, the problem of searching for the eigenvalue of the matrix is solved (Saaty 1980, 1990, 1995), which allows obtaining the vector of normalized, absolute weights of the criteria (sub-criteria) and alternatives. Having determined the preference matrix, the normalization of the results in columns and their summation in rows is performed. Further in Stage II, values of the weights are determined. The next step involves calculating the average in the row, which is the weight of the criterion. Stage III concerns the study of the global consistency of the matrix at each level of the hierarchy, i.e. checking how consistent the preferential information provided by the decision-makers in Stage II is in relation to the criteria (sub-criteria) and alternatives. The validation of the credibility and consistency of the ratings is carried out by calculating one of the two indexes: Consistency Index – CI and/or Consistency Ratio — CR. The smaller the values of the calculated Consistency Index, the more consistent the ratings of the weights of the hierarchy elements. If the values of CI and of the related Consistency Ratio CR at different levels of the hierarchy equal 0, the preferential information provided by the decision-makers at these levels is perfectly consistent. If CI takes the value greater than the permitted one (CI > 0.1), it is necessary to validate the preferential information given by the decision-makers, because it is highly inconsistent. In this case, it is required to go back to Stage II of the algorithm. Step IV involves the final ranking of the alternatives. At this stage, the aggregation of the absolute standardized rankings of weights of the elements in the hierarchy is carried out, using the additive utility function. The result is the final ranking of the alternatives from best to worst, based on their utility value. The value aggregating the utility function is the sum of the products of the absolute weights of the alternative, from the alternative, through the criteria, to the goal. The absolute weights of each matrix are calculated by determining its eigenvector.

2.2. Description of the Electre III method

The Electre III method belongs to the family of Electre methods (from French: **EL**imination **E**t **C**hoix **T**raduisant la **RE**alité). The first approach – Electre I – dates back to the 1960s (Roy 1968). Today, this group also includes Electre I, Electre IV, Electre Is, Electre TRI, Electre IV. It is noteworthy that the Electre III and Electre IV methods are used to solve problems of multiple-criteria ranking (Roy 1990, 1996).

The algorithm of the first one (Electre III), used in solving the problem discussed in this paper, consists of four stages: construction of the weighted matrix (stage I), defining the decision-maker's preferences (stage II), construction of outranking relations (stage III) and creating the final ranking using outranking relations (stage IV).

Hence, the weighted matrix (Stage I) begins with defining a consistent criteria family G rating the finite set of alternatives A. For all the alternatives, the values of individual criterion functions are determined. In stage II (defining the decision-maker's preferences), a preference model is built. To this end, the decision-maker determines the thresholds of: indifference qi, preference pi, veto vi, and criteria weight indexes w_i. In this approach, the following rule applies: $q_i<p_i<v_i$. Then, in Stage III (construction of outranking relations), for each ordered pair (a, b) the following are calculated: the Concordance Index C_i(a,b) rating the degree of credibility that a is at least as good as b, the Discordance Index D_i(a, b) - a measure of denial of the relation that that a is at least as good as b, and the outranking relation defined by the outranking degree S(a, b).

In the last Stage (IV), two complete pre-orders are obtained, referred to as the ascending or descending pre-orders. This stage is based on the alternative ranking algorithm based on the obtained outranking degrees S(a, b). The algorithm is based on the determination of the value satisfying this relation, which is the difference between the number of alternatives that alternative a outranks and the number of alternatives, by which it is outranked. The alternative with the highest qualification index value is located at the top in the descending pre-order. Then, from the remaining alternatives, the best one is selected again and is placed on the subsequent rank in the classification. The procedure is repeated until the alternative set is depleted. The ascending ranking is built analogically, but the procedure starts with the worst solution placed at the end of the ranking. The subsequent procedure is similar to the one employed in the descending ranking, however, in the subsequent iterations, always the worst alternative is selected from those remaining to be considered, and it is placed on the subsequent ascending ranking positions. The final ranking constitutes the final solution and results from the intersection, i.e. the logical quotient, of both pre-orders. Their intersection produces the final ranking. Alternative a is classified higher than alternative b (aPb) if it is better than alternative b in the descending pre-order (or in the ascending pre-order) and not worse than alternative b in the ascending pre-order (or in the descending pre-order). Alternative a is indifferent from alternative b (aIb) if alternative a is indifferent from alternative b in both the descending and the ascending pre-orders. Alternative a is incomparable with alternative b (aRb) if alternative a is better than alternative b in the descending pre-order (or in the ascending pre-order) and worse than alternative b in the ascending pre-order (or in the descending pre-order). The final pre-order is obtained according to the following principle: the best alternative (the one that is not preceded by any other in any of the pre-orders) obtains ranking 1. Ranking 2 is obtained by those alternatives that are preceded by alternatives with ranking 1. Then, subsequent alternatives are ordered. As a result, the final alternative ranking is created where the following relations may occur between the alternatives: indifference (I), outranking (P), reverse outranking (P*) and incomparability (R). The result may be presented in the form of the ranking matrix and/or outranking graph.

2.3. Comparison of the AHP and Electre III methods

Table 1 shows the comparison of the AHP and the Electre III methods. These approaches differ in terms of methodology (some methods are based on the multi-attribute utility theory, and the others are based on the outranking relation), which is impactful on the creation of the decision-maker's and the interveners' preference model. Also, there are various algorithms and rules to create the final rankings as well as the form of their presentation.

Based on the review of the most important features of the compared methods, it is possible to draw the following conclusions (Solecka 2013):
- both methods are related to the problems of ranking the alternatives,
- the AHP and the Electre III methods are user friendly in terms of the procedure algorithm,
- the AHP method is usually applied for small sets of alternatives,
- the Electre III method can be used for both small and large sets of alternatives,
- in the AHP method, in the final ranking, it is possible to identify the quantified distance between the alternatives (which is not possible in the Electre approach),
- in the Electre III method, creating preference models to specify preference thresholds is viewed negatively.

3. Application of the MCDA methods for the assessment of the integrated urban public transportation

3.1. Description of the alternatives

The above-mentioned methods were used to assess the integrated urban public transportation (IUPT) in Cracow. Considering the possible solutions, the alternatives were designed heuristically and compared with the current state (denotation of alternative W0).

Table 1. Comparison of the AHP and Electre III methods

Method	Methodology*	Preference model	Procedure algorithm	Final ranking
AHP	MAUT	Preferences without incomparability, pairwise comparison of criteria, subcriteria, alternatives.	Four stages: (a) – construction of the hierarchical structure of decision-making process – definition of general goals, criteria, sub-criteria, alternatives, (b) – defining the decision-maker's preferences (determined in the scale of 1-9); (c) – calculation of the global consistency; (d) – final ranking of the alternatives.	Ranking of the alternatives based on the calculated utility function; there are two relations between the alternatives**: I and P. Graphical and numerical form of presentation of the results.
Electre III	OR	Defining criteria and local preferences using the weights (w) and thresholds (q – indifference, p – preferences, v – veto).	Four stages: (a) – determining the input data; (b) – construction of the weight matrix, (c) – creating the decision-maker's preference model; (d) – building the outranking relation creating the final rankings.	The final ranking, based on the outranking matrix, includes the relations I, P, R. The final classification in the graphical and numerical form.

(*) MAUT multi-attribute utility theory, OR – outranking relation,
(**) I – Indifference Q – weak preference, P – strong preference, R – Incomparability

In the base alternative – W0 (Fig. 1), the existing transportation system was taken into consideration (Solecka 2013):

- buses: 144 lines (79 urban bus lines and 65 suburban/agglomeration bus lines) with the length of the routes of 924 km and the length of the lines – 1886 km;
- trams: 24 lines of the total length of the routes – – 83 km and the length of the tram lines – 335 km.

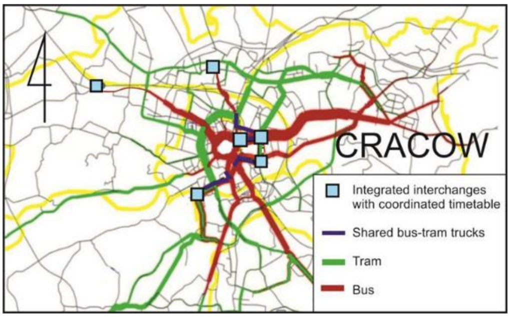

Fig. 1. Graphical presentation and major features of the public transportation system – alternative W0

This alternative characterizes the transportation system that serves approx. 760 thousand residents in the urban zone and approximately 100 thousand residents in the suburban area. The annual number of passengers is approx. 350 million. In the existing alternative, dominate the solutions integrating the urban public transportation, mainly in terms of the spatial and infrastructure integration, which include (Solecka 2013):

- dedicated shared lanes/tracks (the length of approx. 11 km).
- shared bus and tram stops (a total of 27).
- transportation hubs (a total of 6): Mogilskie traffic circle, Grzegorzeckie traffic circle, Cracow Main Railway Station, Krowodrza Gorka, Lagiewniki, Bronowice Male).
- flat fares, combined tickets valid within the agglomeration in different municipalities and tickets integrating rail and urban transportation.

In alternative W0, there is a passenger information system, i.e. a passenger at the stop knows the frequency of service of the public transportation vehicles and receives accurate information on the departures. The existing state assumes the following service frequency: the main bus and tram lines have the frequency of 10 min., the complementary tram and bus lines have the frequency of 20 minutes. For some lines, the interval of 10 minutes during peak hours is increased to 20 minutes beyond these hours. For the main bus lines, it is usually a 15 min. interval during peak hours. There are also lines that run more frequently i.e. every 12, 10 or 8 minutes.

Based on the analysis, for the final considerations compared with the current alternative, 7 new solutions of the integrated urban public transportation in Cracow were adopted, denoted as: W1, W2, W3, W4, W5, W5A, W6. These alternatives were created based on establishing of the course of new routes of the lines of different modes of transportation, and through appropriate modeling of the tools that integrate urban public transportation in the programs for traffic macrosimulation (transportation hubs, shared stops, combined lanes/tracks for buses and trams, combined tickets, combined information, coordination of timetables). These alternatives were differentiated primarily in terms of the occurrence of the tools integrating urban public transportation. Moreover, the frequencies of the service were controlled and the courses of the transportation lines were changed. W1 is the exemplary alternative, shown in Fig. 2.

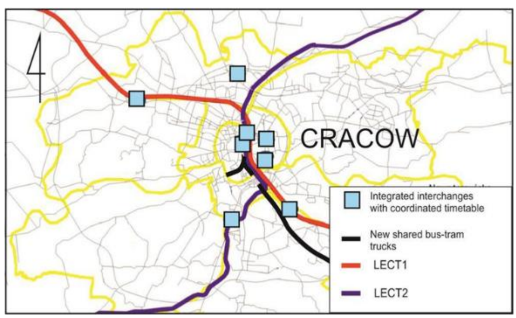

Fig. 2. Graphical representation and major features of the existing public transportation system – alternative W1 (new shared bus-tram truck and LECT)

Alternative W1 is based on the existing system of urban and suburban public transportation, while modifying it slightly. This alternative accounts for the introduction of Light Express City Train (LECT) – 85.95 km, serving the entire agglomeration, i.e. the urban area of Cracow and its adjacent municipalities. Alternative W1 provides for the introduction of two LECT lines that run northeast (Zastow) from the south-west (Skawina) – line LECT1 (46.86 km, 10 stops, travel time of the line – 1 hour 18 minutes) and northwest (Krzeszowice) from the south (Wieliczka) – line LECT2 (39.09 km, 12 stops, travel time of the line – 1 hour 7 minutes). Moreover, this alternative introduced additional bus lines, some bus routes were extended, and some of them modified. The frequency of the bus lines shuttling passengers to transportation hubs was increased. The journey time from the first stop to the center amounts to: for LECT1 – 30 minutes, for LECT 2 – 43 minutes. It was predetermined that LECT would run in the intervals of 15 minutes. Alternative W1 introduced 3 new bus lines aimed at shuttling passengers to transportation hubs: the bus line no. 195 – – Plaszow Railway Station – Prokocim Hospital – – Kurdwanow school – Wola Duchacka – Kabel – – Plaszow Railway Station, the bus line no. 196 – – Biskupice – Main Railway Station – Bronowice Małe, the bus line no. 197 – UJ Campus – Main Railway Station – Mistrzejowice. Alternative W1 contains the following elements integrating urban public transportation:

- dedicated shared lanes/tracks (the length of approx. 18 km);
- shared bus and tram stops (a total of 44);
- transportation hubs (a total of 8);
- combined tickets that are valid in the agglomeration in different municipalities and tickets integrating rail and urban transportation;
- additional information boards with variable content;
- modularity and frequency of the lines leading to the coordination of timetables.

The summary of the specific features of the analyzed alternatives: the existing state (W0) and the proposed alternatives of the integrated urban public transportation in Cracow (from W1 to W6) are demonstrated in Tab. 2 and in Fig. 3 a, b.

As can be seen in Tab. 2, the shortest average travel time, the average travel time and the average time spent in a vehicle of public transportation occur in alternative W4, which is the alternative regarding the tram – train integration. When comparing the average waiting time for a transfer, it can be noted that the preferred variant is alternative W5A, which slightly differs from alternative W4. Most transfer-free journeys are included in alternative W4. The largest number of journeys carried out by passengers using public transportation occurs in alternative W5A that is approx. 5% higher than alternative W0 (with the lowest number of trips). When analyzing the transportation work (Tab. 2 and Fig. 3a,b) expressed in passenger/hour and passenger/km, alternative W3 is clearly the preferred option in terms of the transportation work expressed in passenger/km. In this alternative, passengers spend the least time in the network. In other alternatives, there is a clear increase compared to alternative W3. The smallest transportation work in passenger/km is present in alternative W0, and the largest in alternative W3. The highest average travel speed of the passenger is 24.93 km/h and occurs in alternative W3 (Tab. 2). In the other alternatives, the passenger speed throughout the analyzed system is slightly lower. Alternative W3 enjoyed the highest travel speed due to the presence of the means of public transportation that run entirely on a dedicated track: underground and LECT. Alternative W0 has the lowest average speed of the passenger travel due to the low number of combined, dedicated lanes/tracks for public transportation and a low proportion of intersections with the right of way for public transportation vehicles.

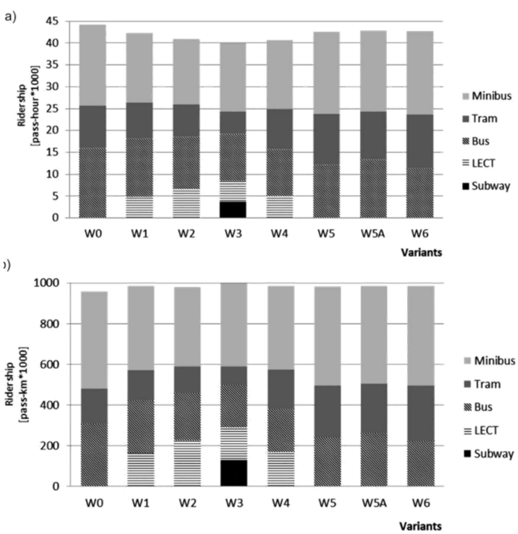

Fig. 3. Comparison of the alternatives of urban public transportation systems in Cracow: a) ridership [passenger/hour], ridership [passenger/km]

Table 2. Comparison of the AHP and Electre III methods

Description		Alternatives							
		W0	W1	W2	W3	W4	W5	W5A	W6
		Status quo - the current level of integration of urban public transportation in Cracow	Bus/rail alternative: integration of high-speed agglomeration rail (LECT) with bus transportation	Rail/tram/bus alternative. Integration of LECT with tram and bus transportation system	Alternative with the underground. Integration of the underground with LECT and with tram and bus transportation system	Tram/rail alternative. Integration of LECT with tram transportation	Tram alternative: integration of tram transportation (Cracow Fast Tram in particular) with bus transportation	Tram alternative: sub-alternative to alternative W5; integration of tram transportation (particularly Cracow Fast Tram)	Dual-mode tram alternative: integration of dual-mode tram transportation
Means of transportation – modal split [% pass/km]	Underground	-	-	-	13	-	-	-	-
	LECT	-	17	23	16	17	-	-	17
	Bus	32	26	24	21	21	24	32	26
	Tram	18	15	13	9	20	26	18	15
	Minibus	50	42	40	41	42	50	50	42
Average passenger speed [km]		22.66	23.30	23.97	24.93	24.22	23.06	22.98	23.11
Average travel time [mm.ss]		45.30	43.27	43.02	42.29	41.52	43.50	42.27	42.29
Average riding time [mm.ss]		33.58	32.27	31.40	31.25	30.58	31.58	31.53	31.33
Average time spent in a vehicle of a public transportation system [mm.ss]		26.05	24.39	23.49	23.16	23.41	24.49	24.55	24.51
Average transfer time [mm.ss]		7.53	8.09						
- at the transfer stop		1.42	1.46	1.52	2.16	1.41	1.41	1.26	1.40
- at first stop		3.36	3.34	3.30	3.23	3.16	3.26	3.15	3.24
Total number of trips/travels		127 465	129 451	129 301	134 174	131 195	131 984	133 481	130 162
No. of passenger trips/travels without transfers		58 869	60 283	60 449	57 943	59 554	58 807	59 348	58 965
No. of passenger trips/travels with transfers		68 596	69 168	68 852	76 231	71 641	73 177	74 133	71 197
No. of passenger trips/travels with 1 transfer		25 899	25 454	24 841	25 287	25 084	26 021	25 851	25 722
No. of passenger trips/travels with 2 transfers		5 301	5 762	5 776	7 711	6 446	6 466	6 744	6 035
No. of passenger trips/travels with >2 transfers		222	242	458	629	531	432	547	410

3.2. Description of the criteria

In order to rate the alternatives, a set of a coherent family of ten criteria was proposed taking into account various stakeholders interested in the selection of a particular alternative of the integrated urban public transportation in Cracow. These criteria are as follows:

Criterion 1: travel time [min] – TP. It secures the social requirements of urban public transportation passengers that include striving for the reduction of travel time from source to destination. It takes into account the average time of reaching the stop, the average waiting time at the stop, the average travel time using public transportation, the average transfer time and the average time of leaving the stop to reach the destination. In order to determine the value of the criterion, it was necessary to determine the significance (weight) of its components. This weight was specified based on the surveys conducted among public transportation experts. This criterion is minimized.

Criterion 2: standard of travel [-] – SP. It takes into account the social needs of urban public transportation passengers by providing passengers with the best travel conditions in an urban public transportation system. It defines the percentage of the travel in good and very good conditions, in all travels using urban public transportation. This criterion takes into account the two essential elements describing the standard of travel: the share of direct travel (no transfers), and the

share of travel in a sitting position, which accounts for the number of passengers that may occupy a seat in the means of urban public transportation. In order to determine the value of the criterion, it was necessary to determine the significance (weight) of its components. This weight was specified based on the surveys conducted among public transportation experts. This criterion is maximized.
Criterion 3: fleet use index [%] – WT. This is a technical criterion allowing an assessment of the effectiveness of the fleet use. It was defined as the quotient of the transportation work performed by the means of public transportation, expressed in passenger/km, to the maximum transportation work realizable by the vehicles of urban public transportation in the analyzed area. This criterion is maximized.
Criterion 4: environment friendliness [%] – PS. It includes the requirements to minimize the harmful environmental impact. It specifies the level of emissions of nitrogen oxides, sulfur dioxide, hydrocarbons, carbon oxides and noise. In order to determine the value of the criterion, it was necessary to determine the significance of the emissions and noise. This weight was specified based on the surveys conducted among public transportation experts. This criterion is maximized.
Criterion 5: the level of integration of urban public transportation [%] – PI. It secures the social requirements of urban public transportation passengers by providing passengers with the most convenient travel conditions with regard to continuity, time, cost and comfort. It defines the level of integration of urban public transportation by taking into account a number of important tools integrating it:
- integrated transportation hubs,
- shared stops,
- availability of a unified, combined passenger information (including transportation network maps for all means of transportation operating in the analyzed area, information boards with variable content at the stops with the information for all means of transportation operating in the analyzed area regarding the timetables, information at the stops and in the vehicles on the possibility of changing the means of transportation),
- flat fares,
- coordination of timetables,
- shared intermodal road sections (e.g. dedicated tracks for buses and trams).

In order to determine the value of the criterion, it was necessary to determine the significance (weight) of its components. This weight was specified based on the surveys conducted among public transportation experts. This criterion is maximized.
Criterion 6: reliability of the urban public transportation system [%] – NS. The essence of the criterion is to ensure the lowest level of faults and the greatest punctuality, which is in the interest of the operator, the public transportation board and the passengers. This criterion is defined as the sum of the shares of the realized shuttles (in accordance with the timetable), the size of which depends on the malfunction of urban public transportation vehicles and the share of timely shuttles dependent on the level of traffic congestion caused by individual vehicles. It is assumed that if a malfunction occurs in the vehicle, the shuttle is not carried out. For the individual components of the criterion, their significance (weight) was defined as well. This weight was specified based on the surveys conducted among public transportation experts. This criterion is maximized.
Criterion 7: safety and security (situational and traffic) [-] – BP. It was expressed with the number of points awarded by the experts defining the level of road safety and situational safety in the urban public transportation system. The criterion takes into account five elements of travel safety:
- the share of vehicles fitted with CCTV,
- the share of stops/hubs fitted with CCTV,
- the share of lengths of the sections of roads and streets dedicated for public transportation vehicles, separated from other traffic (including the lengths of the sections in tunnels and separate tracks),
- the share of collision-free intersections for public transportation,
- the share of lighted stops.

For the individual components of the criterion, their significance (weight) was specified as well. This weight was specified based on the surveys conducted among public transportation experts. This criterion is maximized.
Criterion 8: the profitability of the urban public transportation system [-] – RS. It reflects the synthetic economic and financial efficiency of the urban public transportation system, considering the mutual relations between revenues (from tickets) and the costs generated by the integrated system of urban public transportation. This criterion is maximized.
Criterion 9: availability of the urban public transportation system [-] – DS. It defines the average density

of urban public transportation network in the analyzed area. It is assumed that the greater the total length of the system lines per unit area, the more available the urban public transportation is for the passenger. This criterion is maximized.

Criterion 10: investment costs [PLN] – KI. It is related to the costs of the implementation of nodal and linear infrastructure for urban public transportation. The criterion takes into account the cost of construction of new sections of roads (streets, tracks) for urban public transportation, the cost of building new stops, the cost of construction of integrated transportation hubs, the cost of purchasing of a fleet, the cost associated with fitting stops/vehicles with information systems and the cost of fitting vehicles and stops with CCTV. This criterion is minimized.

The final weighted decision matrix includes Tab. 3.

In order to obtain the necessary values needed to determine the values of each criterion for a finite set of alternatives, individual proposals of the alternatives of the integrated public transportation in Cracow (W1 to W6), together with the existing state (W0), were subjected to a simulation using PTV Visum software.

In the process of modeling of the decision-maker's and the interveners' preferences, two main preferential aspects were taken into account

- the weight of the criteria, the relevance of the criterion for individual entities. They express their subjective impression of the significance of the criteria through weights. The weights of the criteria can be expressed in absolute scale (Electre III), and as relative weight indexes defining the weight of individual criteria based on their pairwise comparisons (AHP).
- sensitivity of the decision-maker and the interveners to changes in the criteria values. Sensitivity to changes in the criteria values means at what considerable values of the criteria, the decision-maker or the interveners begin to differentiate among the alternatives. Sensitivity of the decision-maker and the interveners to changes in the criteria are defined by preference thresholds: q – indifference, p – preference, v – veto, for each criterion in the III Electre method or by using relative weight indexes for the pairwise compared alternatives with respect to each criterion – the AHP method.

3.3. Decision-maker's preference model and final rankings using the Electre III method

The values of the criteria weights and the values of the sensitivity to their changes in the criteria values were defined based on the surveys conducted among passengers. The obtained results are shown in Tab. 4.

Computational experiments using the Electre III method have been carried out using the software package Diviz 1.15.1. For this purpose, Electre III was developed using specific modules. The most important of them are as follows:

- module of computing concordance relation,
- module of computing discordance relation per criteria,
- module of cut-off threshold,
- module of ascending and descending distillation and their cut-off level

Table 3. Weighted decision matrix

Alternative	TP*	SP**	WT**	PS**	PI**	PI**	NS**	BP**	RS**	DS**	KI*
	[min]	[-]	[%]	[%]	[%]	[%]	[-]	[-]	[%]	[-]	x 1000 [PLN]***
W0	53.32	0.456	50.14	0	25.90	0.00	92.8	0.19	-26	1.61	0
W1	51.65	0.495	48.77	49	37.69	42.57	93.4	0.39	-24	1.69	432 892
W2	51.02	0.550	38.84	59	45.88	72.15	93.5	0.40	-34	1.75	955 630
W3	50.84	0.506	43.01	78	31.20	19.15	93.6	0.57	-31	1.69	9 685 460
W4	49.45	0.519	47.34	57	32.73	24.64	93.5	0.53	-33	1.71	1 459 193
W5	50.93	0.487	47.23	81	50.68	89.45	93.4	0.59	-30	1.67	1 958 287
W5A	50.11	0.582	41.80	100	44.22	66.14	94.1	0.57	-48	1.53	2 678 189
W6	50.22	0.501	46.68	64	53.60	100.00	92.8	0.60	-34	1.69	2 128 785
(*) – minimized criterion, (**) – maximized criterion (***) – PLN polish zloty 1 USD = 3.6 PLN											

Source: based on Solecka (2013)

Table 4. Passenger's preference model expressed by the weights of the criteria and the threshold values in the Electre III method*

No.	Criterion	Weight of the criterion [-]	Value of thresholds:		
			Indifference (q)	Preference (p)	Veto (v)
1.	TP	6.44	0.05	0.9	1.8
2.	SP	5.44	0.008	0.050	0.100
3.	WT	2.93	3	8	15
4.	PS	3.97	15	25	50
5.	PI	6.17	3	5	10
6.	NS	6.33	0.02	0.04	0.1
7.	BP	6.00	0.05	0.08	0.15
8.	RS	1.83	15	18	20
9.	DS	6.13	0.03	0.05	0.1
10.	KI	2.03	3	7	9

(*) Criteria weight values and values of sensitivity to criteria weight changes were determined on the basis of surveys performed among entities interested in the problem as well as among public transportation experts

As a result of the performed computational experiments, rankings of the alternatives within the ascending and descending distillations were obtained. Tab. 5 demonstrates the individual items. As can be seen in both the first and the second distillation, the alternative presenting the current state is in the lowest position. Alternative W5 is in the highest position. There are also cases where in the descending distillation the alternative is highly ranked and in the ascending distillation the alternative is low or vice versa (e.g. W5A or W4).

Table 5. Passenger's preference model expressed by the weights of the criteria and the threshold values in the Electre III method

Alternative	Position of the alternative in the descending distillation	Position of the alternative in the ascending distillation
W0	7	8
W1	6	7
W2	2	1
W3	3	1
W4	3	5
W5	1	1
W5A	7	1
W6	3	5

The final rankings were obtained following the cut-off of the descending and ascending distillations. Fig. 4 shows the rankings resulting from the adoption of different cut-off thresholds. In Fig. 4a, the cut-off threshold was 0.4. On the other hand, the ranking in Fig. 4b was obtained for the thresholds from 0.5 to 0.7 and in Fig. 4c for the cut-off thresholds of 0.8.

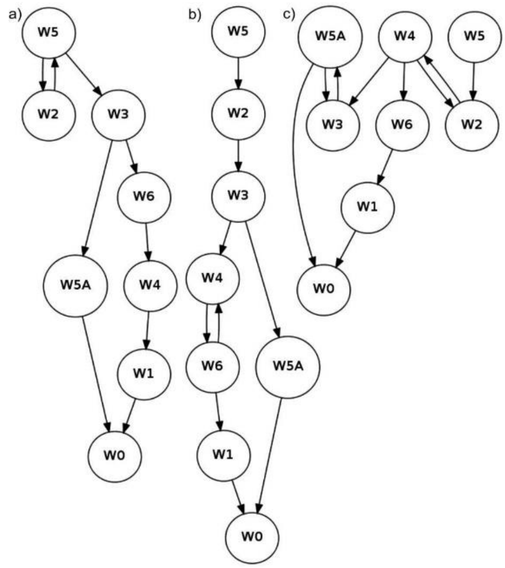

Fig. 4. The final ranking of the alternatives obtained by the Electre III method in Diviz software for different values of the cut-off thresholds s(l): a) 0.4; b) 0.5-0.7, c) 0.8

In the final ranking generated by the Electre III method, from the passenger's point of view, the best solution turned out to be alternative W5 receiving the highest ranking in all of the adopted values of the cut-off threshold. The lowest position was held by the current alternative – W0.

As a result of the computational experiments conducted by the Electre III method, it is possible to obtain the final ranking: W5, W5A, W6, W4, W2, W3, W1, W0, (where W5 represents the best, and W0 the worst alternative).

3.4. Decision maker's preference model and the final rankings using the AHP method

The computational experiments using AHP were carried out using the Expert Choice program. Based on the preferential information on pairwise compar-

isons of the criteria, their relative weights were obtained in the scale of 1-9 points characteristic of the AHP method. The decision-maker's preferences determined in this way, referring to the weights of the analyzed rating measures, are illustrated in Fig. 5. The values presented in black denote the prevalence of the criterion located on the left over the criterion located on the right. The values presented in red denote the prevalence of the criterion located on the right over the criterion located on the left.
Additionally, the absolute weights of individual criteria were calculated (Fig. 6). The highest weight was obtained by the TP criterion, while the lowest – – by the RS criterion.

Subsequently, the decision-maker's sensitivity to the changes in the values of the criteria was determined, defining the relative weight indexes for the alternatives subjected to pairwise comparisons with respect to each criterion. In this way, the matrices of relative weights were obtained for each criterion. An example of such a matrix for the TP criterion – travel time, is shown in Fig. 7.
The final ranking of the alternatives relative to the TP criterion is presented in Fig. 8 (a clearly visible distance between the alternatives; it is easy to indicate how much better a given alternative is).

	TP	SP	WT	PS	PI	NS	BS	RS	DS	KI
TP		3,0	7,0	5,0	2,0	1,0	2,0	9,0	2,0	9,0
SP			5,0	3,0	3,0	3,0	2,0	7,0	2,0	7,0
WT				3,0	6,0	6,0	6,0	3,0	6,0	3,0
PS					4,0	4,0	4,0	4,0	4,0	5,0
PI						1,0	1,0	9,0	1,0	8,0
NS							2,0	9,0	2,0	9,0
BS								8,0	1,0	8,0
RS									9,0	2,0
DS										8,0
KI		Incon: 0,03								

Fig. 5. Passenger's preference model in the AHP method

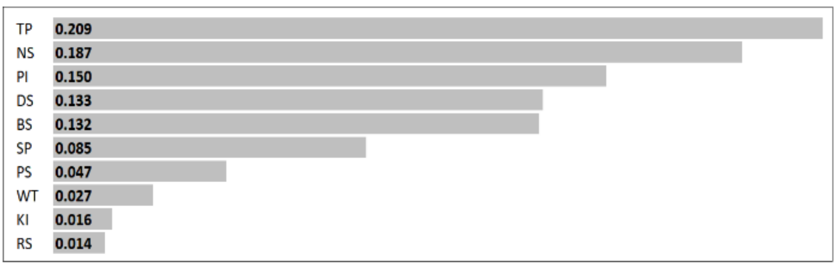

Fig. 6. Absolute weight (use) indexes of the criteria obtained by the AHP method

	W0	W1	W2	W3	W4	W5	W5A	W6
W0		2,0	3,0	4,0	6,0	3,0	5,0	5,0
W1			1,0	2,0	3,0	1,0	2,0	2,0
W2				1,0	2,0	1,0	2,0	2,0
W3					2,0	1,0	1,0	1,0
W4						2,0	1,0	1,0
W5							2,0	1,0
W5A								1,0
W6		Incon: 0,01						

Fig. 7. Comparison of the alternatives in relation to the TP criterion

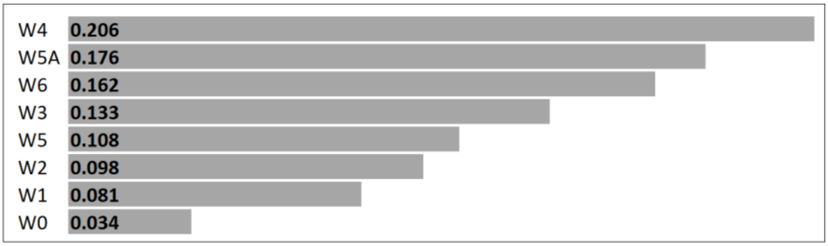

Fig. 8. Ranking of the alternatives in relation to the TP criterion

The best alternative in terms of the TP criterion turned out to be W4. The comparison of the alternatives in relation to the other criteria was carried out analogically.

The global consistency of the matrix was also studied at each level of the hierarchy. The Consistency Index of all considered matrices did not exceed 0.1 - that means the consistency of information. In the last Stage, the global use of all alternatives was calculated and they were ranked in order from best to worst (Tab. 6 and Fig. 9). The values in the final ranking were standardized in such a way that the value of 1 was assigned to the greatest value of the utility function for a given alternative, for the other ones — respective proportions were expressed.

The computational experiment conducted by AHP from the point of view of the passenger's expectations demonstrated that the most preferred solution of the Integrated System of Urban Transportation System in Cracow is alternative W5A and the least favorable – alternative W0. In the final ranking, it can be observed that there is a small prevalence of alternative W5A over alternative W6.

4. Conclusions and recommendations

The final rankings were obtained following the computational experiments performed by the two methods. The summary results are presented in Fig. 10. The results obtained by the two methods prove that alternative W5 and subvariant W5A were the best alternatives, while W1 and W0 turned out to be the worst ones.

The winning alternatives (W5 and W5A) are focused on the development of rail transportation, particularly trams and have an extended network of the fast tram lines (W5 vs. W5A: the same means of transportation, different numbers of bus and tram lines).

Tab. 6 Matrix of the function of the use of the alternatives in relation to individual criteria

Ideal mode		PAIRWISE									
Alternative	Total	TP (G: 0.209)	SP (G: 0.085)	WT (G: 0.027)	PS (G: 0.047)	PI (G: 0.150)	NS (G: 0.187)	BS (G: 0.132)	RS (G: 0.014)	DS (G: 0.133)	KI (G: 0.016)
W0	0.177	0.167	0.068	1.000	0.550	0.068	0.217	0.068	1.000	0.124	1.000
W1	0.289	0.395	0.146	0.607	0.126	0.210	0.287	0.110	0.681	0.383	0.704
W2	0.478	0.476	0.064	0.099	0.257	0.467	0.375	0.167	0.374	1.000	0.541
W3	0.395	0.646	0.273	0.250	0.492	0.092	0.471	0.361	0.318	0.396	0.060
W4	0.478	1.000	0.388	0.576	0.207	0.127	0.342	0.242	0.258	0.658	0.290
W5	0.434	0.524	0.091	0.576	0.638	0.665	0.264	0.642	0.336	0.230	0.168
W5A	0.639	0.851	1.000	0.159	1.000	0.400	1.000	0.463	0.086	0.112	0.085
W6	0.607	0.787	0.255	0.360	0.400	1.000	0.287	1.000	0.180	0.396	0.118

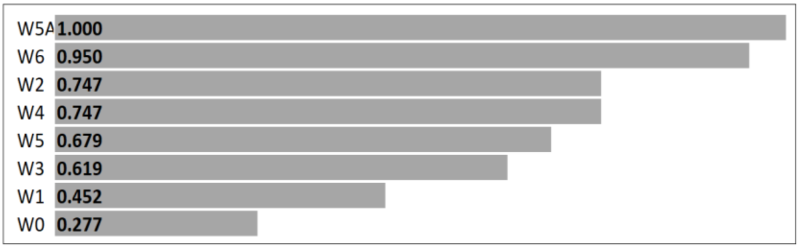

Fig. 9. Final ranking of the alternatives obtained using the AHP method

The alternatives that must be rejected are W0, W1, W3. The main features decisive of their low position include: low reliability of the system, low level of travel security, long travel time, low standard of travel, low level of environment friendliness and high investment costs. The presented methods are extremely useful in solving the problems of transportation and the final results point to the desired course of action.

Fig. 10. The final results (ranking from best to worst) obtained by the Electre III and AHP methods

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